PROCEEDINGS OF SCIENCE

Cold and Ultra-cold Neutrons as Probes of New Physics

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Despite the great success of the Standard Model, many key questions in particle physics, astrophysics, and cosmology are unanswered. In particular, more than 95 % of the universe consists of unknown dark matter and dark energy. Today, a major goal of particle physics is to look for evidence of new physics beyond the Standard Model. Collider searches for new physics are well suited to the direct production of new high-mass particles, whereas low-energy precision experiments search for traces that new particles leave in known processes. Direct and indirect evidence of new physics are highly complementary.

High-precision experiments with extremely slow, cold and ultra-cold neutrons address some of the unanswered questions, for instance, on the nature of the fundamental forces and underlying symmetries, the origin, evolution, and fate of the universe, or on the nature of the gravitational force at very small distances. For example, the limit on the electric dipole moment of the neutron constrains the CP violating phases, the lifetime of the neutron determines the relative helium abundance in the universe, and neutrons bouncing over a mirror probe dark matter and dark energy.

New facilities and technological developments now give window for significant improvement in precision by one to two orders of magnitude. In this paper, we will give an overview of current and planned facilities and experiments, as well as an overview of some of the applications of neutrons to astrophysics, cosmology, and physics beyond the Standard Model.

The 26th International Nuclear Physics Conference
11-16 September, 2016
Adelaide, Australia

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1. Introduction

In recent years, cosmic surveys have revealed the composition of the universe [1, 2]: The today's universe consists of 69.4(8) % dark energy, 25.8(8) % dark matter, and of 4.8(1) % ordinary matter [2, 3]. However, 'the missing link in cosmology is the nature of dark matter and dark energy', as Stephen Hawking said at Caltech in 2013, where he lectured on the origin of the universe.

At present, the Standard Model is the best description of all known particles and their interactions. But it does not explain gravity, dark matter and dark energy, neutrino masses, or the baryon asymmetry of the universe. New physics beyond the Standard Model is needed to explain these deficiencies. Theories beyond the Standard Model include extensions of the Standard Model through, e.g., supersymmetry or entirely novel explanations such as, e.g., extra dimensions.

Physicists worldwide wonder what dark matter is. Potential dark matter candidates include

- weakly interacting massive particles (*WIMP*). The supersymmetric particle neutralino is the most favored candidate for dark matter.
- *axions*. Only axions of a specific, low mass could explain the invisible nature of dark matter.
- massive astrophysical compact halo objects (*MACHO*). MACHOs like black holes, neutron stars, and brown and white dwarfs are composed of ordinary matter.
- *extra dimensional dark matter*. The lightest Kaluza-Klein particle in universal extra dimensions is an excellent candidate for dark matter.
- *gravitinos*. The gravitino is the superpartner of the hypothetical graviton, which in turn mediates the gravitational force.
- *sterile neutrinos*. Sterile neutrinos may be neutral heavy leptons.
- *mirror world dark matter*. Mirror matter is the oldest but still viable candidate for dark matter.

We use cold and ultra-cold neutrons (see Sect. 2 for definition and Sect. 3 for neutron sources) to unravel this and other open questions in particle physics, astrophysics, and cosmology [4, 5, 6]. For instance, the about eight seconds discrepancy between the 'bottle' and 'beam' averages of the neutron lifetime [7] could be explained by new physics. Further applications are found in Sect. 4.

'Bottle' experiments store ultra-cold neutrons in a material or magnetic trap and count how many are left after a given time. 'Beam' experiments direct a stream of cold neutrons through an electromagnetic trap and count the trapped decay protons within a given time. Assume that neutrons would disappear via beta decay and a second, previously unknown process. Then 'bottle' experiments would record both processes, whereas 'beam' experiments would record only beta decay. 'Bottle' experiments would therefore result in a shorter neutron lifetime, as observed in the experiments.

Although experimentalists think that one or even both neutron lifetime experiments have underestimated or overlooked a systematic effect, a few theorists have suggested a second process which may explain an anomalous loss of stored neutrons. Berezhiani and Nesti hypothesized the existence of a parallel world consisting of mirror particles. According to their hypothesis, each neutron could oscillate into its invisible twin from the parallel world, the so-called mirror neutron [8, 9]. The discovery of neutron–mirror neutron oscillations may also shed light on the nature of dark matter, and would be a discovery of the baryon number violation ($\Delta B = 1$).

2. Properties of the neutron

The neutron, n, is a subatomic particle with, according to its name, no net electric charge. It is made up of two down quarks and one up quark, and reacts to all known forces. The key properties of the neutron are summarized in Table 1. Because of these unique properties, neutrons are a

Quantity	Symbol	Value
Charge	q_n	$< 1 \times 10^{-21}$ e
Radius	r_n	~ 1 fm
Mass	m_n	$939.5654133(58)\,\mathrm{MeV/c^2}$
Mass difference	$m_\mathrm{n} - m_\mathrm{p}$	$1.29333205(51)\,\mathrm{MeV/c^2}$
Lifetime	τ_n	$880.2(1.0)$ s
Spin	I	$1/2$
Magnetic dipole moment	μ_n	$-1.91304273(45)\,\mu_\mathrm{N}$
Electric dipole moment	d_n	$< 3.0 \times 10^{-26}$ e·cm
Electric polarizibility	α_n	$118(11) \times 10^{-5}\,\mathrm{fm^3}$
Magnetic polarizibility	β_n	$37(12) \times 10^{-5}\,\mathrm{fm^3}$

Table 1: Key properties of the neutron according to the 2016 PDG review [3].

powerful tool for investigating almost all kinds of matter. For example, neutrons can penetrate non-destructive and deep into matter, as they are electrically neutral. Hence, neutrons are applied not only in particle physics but also in physics, nuclear physics, chemistry, crystallography, materials sciences, biology, medicine, geosciences, archaeology, and art history. As a result, the number of neutron research facilities worldwide (see Sect. 3) is abundant.

Neutrons as such cannot be distinguished. But their energy and wavelength or magnetic properties must be adapted to the specific application. Thus, it is common to distinguish neutrons according to their energy. Table 2 shows their energy classification. In particular, neutrons which are reflected under all angles of incident are called ultra-cold neutrons (UCNs).

Energy [meV]	Wavelength [Å]	Velocity [m/s]	Temperature [K]	Classification
$< 3 \times 10^{-4}$	> 520	5	2×10^{-3}	Ultra-cold neutrons
$0.1 - 20$	5	800	40	Cold neutrons
25	1.8	2200	300	Thermal neutrons
$40 - 10^3$	0.7	5700	2000	Hot neutrons
2×10^9	2×10^{-4}	2×10^7	2×10^{10}	Fission neutrons

Table 2: Energy classification of the neutron. The limits are slightly different from source to source.

3. Neutron research facilities

Around the world, there are 41 neutron research facilities in operation: nine in North America, three in South America, eight in Asia, 19 in Europe, and one each in Africa and Australia. Each of these facilities operates a large-scale neutron source. In addition, two more facilities are currently under construction: the China Spallation Neutron Source (CSNS), with operation planned for 2018, and the European Spallation Source (ESS) in Lund/Sweden, with operation planned for 2023.

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Neutrons are produced by nuclear fission in research reactors or by spallation in accelerator-driven spallation sources. In research reactors, a fissile nucleus (^{235}U or ^{239}Pu) captures a neutron, splits into two lighter nuclei, and releases two to three free neutrons. This corresponds to one to two useable neutrons per fission. In spallation sources, high-energy protons from the accelerator are focused onto a heavy metal target (Hg, W, Ta, or Pb), collide with the target nuclei, and leave highly excited nuclei. The excited nuclei, in turn, lose their energy by emitting protons and predominately neutrons, 30 to 40 per proton. However, the time-averaged neutron flux of existing spallation sources is inferior to that of research reactors, because spallation sources run in connection to a pulsed particle accelerator. At present, the Institut Laue-Langevin (ILL) in Grenoble/France operates the most intense neutron source in the world. But once operational, the ESS will be the first pulsed neutron source with a higher time-averaged flux than the ILL (cf. Table 3).

Fission and spallation neutrons have average energies of about 2 MeV (see Table 2), which are far too high for our applications in particle physics. These neutrons are therefore slowed down in moderators and in so-called secondary sources arranged around the primary neutron source. Moderators like graphite or heavy water, D_2O, are used to provide hot respectively thermal neutrons. Secondary sources filled with liquid hydrogen, H_2 or D_2, at a temperature of $20-30$ K, imbedded in the heavy water moderator, produce cold neutrons. Table 3 lists the cold neutron beam lines for particle physics. We note that the NIST beam line has been improved by more than a factor of 4,

Name	Facility	Pulsed	Time-averaged capture flux density [$\times 10^9$ n/cm^2/s]	Comment
ANNI	ESS	Yes	50	proposed
PF1B	ILL	No	20	
MEPHISTO	FRM II	No	18	under construction
NG-C	NIST	No	8.3	
FnPB	SNS	Yes	3.8	
FP12	LANSCE	Yes	0.1	
NOP	J-PARC	Yes	1.2/MW	

Table 3: Flux of existing and proposed cold neutron beam lines for particle physics [5, 10, 11, 12, 13].

and that ANNI, the beam facility proposed for ESS [14], would exceed the time-averaged flux of the most intense continuous beam lines and provide, at full flux, all advantages of a pulsed facility.

The most well-known UCN source is the so-called Steyerl neutron turbine at the ILL, which was installed in 1986: A beam of very cold neutrons (VCNs) with velocities of 50 m/s is extracted from the ILL's vertical cold source by a slightly curved vertical neutron guide. UCNs are then produced by a Doppler shifter. The Steyerl turbine with 690 cylindrically curved blades rotates at a speed of 25 m/s and decelerates the VCNs into the UCN energy range ($0-15$ m/s) [15].

In the 1990s, worldwide efforts to increase UCN intensities and densities started. The trend today is towards so-called superthermal UCN sources: Thermal or cold neutrons are inelastically scattered on a medium and transfer their energy to an excitation of the scattering medium, for instance, to a phonon. In this way, neutrons are 'down-scattered' to the UCN energy range. Superthermal UCN sources based on superfluid helium, LHe, provide long storage times, while sources based on solid deuterium, SD_2, provide high production rates.

Besides the Steyerl turbine, two LHe sources and three SD_2 sources are currently operating at the ILL [16], RCNP/KEK [17], LANSCE [18, 19], PSI [20], and at the TRIGA Mainz [21]. For a recent comparison see Ref. [22]: UCN densities range from a few UCN/cm^3 at the TRIGA Mainz to 22 UCN/cm^3 at the PSI. In addition, three more LHe sources and two more SD_2 sources are under construction at the ILL, TRIUMF/KEK, PNPI [23], FRM II, and at the PULSTAR reactor [24]. According to calculations, the new sources will exceed the UCN densities of the 'old' sources by up to three orders of magnitude (see also Ref. [19]). Future experiments could thus significantly gain in precision, by one to two orders of magnitude, and would no longer be limited in statistics.

4. Fundamental neutron physics

As we have just seen, the number of neutron research facilities and UCN sources worldwide has increased considerably. Hence, there are more and more opportunities to study the fundamental properties and interactions of the neutron. In neutron particle physics, we are concerned with

- *neutron oscillations*. As addressed in Sect. 1, the discovery of neutron–anti-neutron, $n\bar{n}$, or neutron–mirror neutron, nn', oscillations would be a discovery of baryon number violation ($\Delta B = 2$ resp. 1). The best limits for $n\bar{n}$ oscillations stem from bound neutrons inside nuclei [25, 26]. Present limits for $n\bar{n}$ and nn' oscillations from free neutrons are from 1994 [27] respectively the late 2000s [28, 29, 30]. New experiments are proposed at the SNS [31], PNPI [32], and at the ESS [14, 33]. See Ref. [34] for a recent review.
- *neutron beta decay* (see Sect. 4.1 and Refs. [35, 36] in this proceedings),
- *the neutron electric dipole moment* (nEDM). The discovery of a permanent nEDM could shed light on the baryon asymmetry of the universe, and would be a clear sign of a new CP violating interaction beyond the Standard Model, at the TeV or even PeV scale [37]. Recently, a revised upper limit on the value of the nEDM [38] and a new search for the nEDM at ILL [39] have been presented. A new limit from the nEDM experiment at PSI is expected in the near future [20]. In addition, six more experiments are under construction at the RCNP/TRIUMF, FRM II, SNS, PNPI, LANSCE, and at the PSI, and three new ones are proposed for the PIK reactor, J-PARC, and for the ESS [40]. Essentially all of them aim at one to two orders of magnitude improvement. For recent reviews see Refs. [37, 41, 42].
- *the gravitational force at very small distances* (see Sect. 4.2),
- *neutron interferometry* (cf. Sect. 4.2.1). Groups at NIST [43] and Atominstitut/ILL [44, 45] employ neutron interferometry primarily for fundamental tests of quantum mechanics [46].
- *the neutron charge*. There is no reason to assume that the neutron is electrically neutral. A non-zero charge could be explained by extra dimensions, superstrings, or other grand unified theories. Groups from Mainz [47] and Vienna [48] aim to improve the limit from 1988 [49].
- *neutron scattering*. Neutron scattering data constrain extra-short-range forces [50], and neutron crystal-diffraction constrains a spin-dependent short-range interaction [51].
- *hadronic weak interactions*. Hadronic parity violation is a unique probe of the non-perturbative strong coupling limit of QCD. The NPDGamma Collaboration just presented preliminary results on the long range weak meson coupling h^1_π [52], which will finally test theoretical predictions [53, 54, 55]. The n+^{3}He experiment at SNS continues this study, and a new n+^{4}He apparatus is under construction for NIST [56]. See Refs. [57, 58, 56] for recent reviews.

- *reactor neutrinos*. In 2011, an anomaly in reactor antineutrino spectra has been revealed [59, 60]. This and other anomalies found in neutrino oscillation experiments could be explained by a light sterile neutrino. Serebrov *et al.* just reported on the first ever measurements with *moving* NEUTRINO-4 *detector* at the SM-3 reactor [61]. First results of the STEREO experiment at the ILL are expected for 2017 [62]. See Ref. [63] for a more general review.

Here, we focus on *neutron decay*, the *gravitational force*, and *neutron interferometry*. For the other applications see Refs. [20, 64, 65, 66, 67, 68, 69, 70] in this proceedings and recent reviews [4, 5, 6].

4.1 Neutron beta decay

Free neutrons decay into a proton, an electron, and an anti-electronneutrino, with a mean lifetime $\tau_\mathrm{n} \approx 15\,\mathrm{min}$. (cf. Table 1). The differential decay probability can be parametrized by angular correlation coefficients [71]. For example, the beta asymmetry parameter A describes the angular correlation between the neutron spin and the electron momentum. In this way, more than 20 observables can be defined. These correlation coefficients depend differently on the vector, axial vector, scalar, tensor, and pseudo-scalar weak coupling constants.

In the Standard Model, all correlation coefficients depend only on the ratio $\lambda = g_\mathrm{A}/g_\mathrm{V}$ of the axial vector to the vector coupling constant, whereas the neutron lifetime depends on λ and the CKM matrix element V_ud. Hence, measuring several correlation coefficients precisely allows testing the Standard Model and limiting or identifying non-Standard Model couplings.

Interactions beyond the Standard Model can be best constrained from tests of the unitarity of the CKM matrix. Extensions of the Standard Model like supersymmetry or entirely new physics concepts like leptoquarks predict new physics at the TeV scale. Testing new physics at mass scales of 1 to 100 TeV through neutron decay requires high-precision measurements with 10^{-4} accuracy.

Not to forget, the values of g_A and τ_n are important for predictions in cosmology (primordial abundances of light elements) and astrophysics (solar neutrino flux, neutron star formation), applications in particle physics (spin content of proton, Goldberger-Treiman relation, detection efficiency of neutrino detectors), and for computational physics (lattice benchmark, see Sect. 4.1.4).

See Refs. [4, 5, 72] for recent reviews and theoretical prospects.

4.1.1 The neutron lifetime puzzle

As introduced in Sect. 1, the 2016 PDG average of the neutron lifetime $\tau_\mathrm{n} = 880.2(1.0)$ s consists of five 'material bottle' plus two 'beam' experiments [3]. Its 1 s uncertainty is far greater than the 0.1 s sensitivity required for new physics searches, and is dominated by the ~ 8 s discrepancy between the two methods. Although earlier experiments have been reanalyzed [73, 74, 75] since the present best resulted $\tau_\mathrm{n} = 878.5(8)$ s [76], the discrepancy could not yet be resolved. We note that the most precise 'magnetic storage' experiment [77] is not included in the PDG average.

In order to finally resolve the discrepancy, not only existing 'bottle' and 'beam' projects are continued, but also alternative methods of measuring the neutron lifetime are being developed worldwide: A new 'beam' experiment at J-PARC will detect the decay electrons rather than the decay protons [35], and new 'bottle' experiments at ILL [78, 79], PNPI [23], LANSCE [80, 81, 82], FRM II [83, 84], and TRIGA Mainz will confine UCNs with magnetic fields rather than material walls. These experiments aim at accuracies of 1 down to 0.1 s.

For recent reviews see Refs. [85, 19, 7].

4.1.2 Angular correlation coefficients

The 2016 PDG average of the weak coupling constants ratio $\lambda = -1.2723(23)$ comprises seven measurements of correlation coefficients in neutron decay [3]. The most precise published measurements have reached accuracies of a few times 10^{-3} for beta A [86, 87, 88] and neutrino asymmetry parameters B [89, 90] and on the percent level for proton asymmetry parameter C [91] and electron-neutrino correlation coefficient a [92, 93]. The Fierz interference term b has not yet been resolved in neutron decay, but is promising for probing scalar and tensor interactions [94, 95].

In order to improve the precision of neutron decay correlations, several new instruments have been built or are presently under construction worldwide: aSPECT [96, 97, 98, 99], aCORN [100, 101], PERKEO III [102], UCNb [103], UCNB [104, 105], Nab [106, 107, 108], PERC [109, 110]. New results for a and A from aSPECT [111], aCORN [112], and PERKEO III are expected soon.

PERC is a particular new concept: charged decay products are collected from a neutron guide, magnetically filtered and transported to a secondary spectrometer. The R$\times$B spectrometer NoMoS as first secondary spectrometer is already under development [113]. It uses a novel concept to measure the momentum dependent drift of charged particles in a curved magnetic field [114]. This unique combination will open the door to reach 10^{-4} sensitivity in neutron decay. An optimized and extended electron-proton/neutron separator has been proposed with ANNI (see also Ref. [115]).

Today's experiments are mainly limited by statistics and the knowledge of polarization (in the case of asymmetries), background, and spectrometer response. As regards polarization, it has been demonstrated that neutron polarimetry with opaque ^{3}He cells can reach 10^{-4} accuracy [116, 117, 118], and a novel solid-state polarizer concept has been proposed recently [119]. As regards detectors, the trend is away from plastic scintillators and towards silicon detectors [120]. However, in order to effectively suppress background the two detectors principle is still favoured [121].

See Refs. [4, 5, 122, 19] for recent reviews.

4.1.3 Rare decay modes

A small fraction, of a few per mill, of the neutron decays is accompanied by the emission of a photon. Over the past 10 years, the branching ratio for this radiative decay mode has been substantially improved [123, 124]. The RDK II Collaboration recently reported on the first precision test of the shape of the photon energy spectrum [124]. Future precision measurements of the radiative decay mode can probe new physics. For example, the measurement of a T-odd momentum correlation between photon, electron, and anti-electronneutrino would constrain new spin-independent sources of CP violation, which are not constrained by the non-observation of permanent EDMs [125, 126].

A very small minority, of a few per million, of the neutrons is expected to decay into a hydrogen atom and an anti-electronneutrino. Although already predicted by Nemenov in 1980 [127], this bound state decay mode has not yet been observed. The planned BoB experiment aims to discover this rare decay mode, and to improve the limits on the scalar and tensor coupling constants as well on the mass and mixing angle of a boson mediating right-handed interactions [128, 129].

4.1.4 Theoretical considerations

Despite its importance, the value of g_{A} is theoretically known only to several percent, but considered as benchmark for lattice QCD [130]. New lattice groups have been formed to calculate challenging non-perturbative QCD observables such as the nucleon form factors g_{A}, g_{S}, and g_{T}

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[131]. A new $1-2\,\%$ accurate value of g_{A} is expected within the next years. In addition, EFT [132] and most recently Dyson-Schwinger equations [133] are used to calculate these quantities.

Not least, new physics searches with 10^{-4} sensitivity need adequate input from theory: the existing analysis of correlation coefficients a, A, B, C, and D [134] must be extended to order 10^{-5}, and completed with non-standard correlation coefficients G, N, Q, R [135], and L to order 10^{-3}.

4.2 Test of gravitation with quantum interference

4.2.1 Gravitation and Neutron interferometry

The whole class of neutron interferometry experiments and the material on quantum interference phenomena is covered in the review on 'Neutron Interferometry' [46]. In 1975, Colella, Overhauser, and Werner demonstrated in their pioneering work [136] a gravitationally induced phase shift in a neutron interferometer experiment. This experiment was carried out at the Ford Nuclear Reactor in Ann Arbor at 2 MW and the signal is based on the interference between coherently split and separated neutron de Broglie waves in the gravity potential. The interferometer is turned around the incident beam direction by an angle ϕ maintaining the Bragg condition.

The history of gravity-induced interference experiments is described in Ref. [46]. The comparison between theory and experiment shows that the agreement was poor. In a recent paper, Heacock *et al.* show that the dynamical phase correction is attenuated by slight, intrinsic misalignments between diffracting crystals, potentially explaining the long-standing 1 % discrepancy between theory and experiment [137].

4.2.2 The quantum bouncing ball

Above a mirror, the gravity potential leads to discrete energy levels of a bouncing massive particle. The corresponding quantum mechanical motion of a massive particle in the gravitational field has been named the quantum bouncer [138, 139, 140, 141]. The discrete energy levels occur due to the combined confinement of the matter waves by the mirror and the gravitational field. For neutrons the lowest discrete states are in the range of several peV, opening the way to a new technique for gravity experiments and measurements of fundamental properties.

The first observation of quantum states in the gravitational potential of the earth with UCNs [142, 143, 144, 145] has been performed at the ILL. The *q*BOUNCE collaboration developed a resonance-spectroscopy technique to probe these energy eigenstates by coupling the quantum-system to an external resonator. Quantum mechanical transitions with a characteristic energy exchange between the coupling and the energy-levels are observed on resonance. A novelty of this work is the fact that the quantum mechanical transition is driven by an oscillating field that does not directly couple an electromagnetic charge or moment to an electromagnetic field. Instead, the energy transfer is provided by an oscillating mirror. The collaboration named this technique Gravity Resonance Spectroscopy [146], because the energy difference between these states has a one-to-one correspondence to the frequency of the modulator, in analogy to the nuclear magnetic resonance technique, where the energy splitting of a magnetic moment in an outer magnetic field is related to the frequency of a radio-frequency field. This is possible because of the feature of the quantum bouncing ball that the levels are not equidistant in energy. A plan is to apply Ramsey's method of separated oscillating fields to the spectroscopy of the quantum states in the gravity potential above a horizontal mirror [147]. The GRANIT Collaboration aims for observing resonant transitions by using spatially oscillating magnetic fields [148, 149, 150, 151]. Evidence for states in a coherent superposition can be found in Refs. [138, 152, 153]. For a measurement of the probability to find a neutron on the mirror with spatial resolution detectors have been developed [154] based on ^{10}B converters used in the *q*BOUNCE experiments.

4.2.3 Limits on hypothetical gravity-like interactions

With the *q*BOUNCE experiment, gravity at short distances of microns is examined. Deviations can arise for example due to large extra dimensions or any yet unknown model. The additional force would be sourced by the bottom mirror in region II and leads to an additional potential seen by the neutron. As a result, the energy of the states would be shifted in a characteristic way. This would be detectable as an energy shift of the transitions. The axion would also provide a spin-mass coupling, which is examined with neutrons but covered by the review.

A recent review on neutrons as a probe for dark energy can be found in Ref. [155]. Dark energy candidates are so called chameleon fields [156, 157]. The chameleon is a candidate for dark energy owing its name to the screening effect. This screening effect ensures that the chameleon field is suppressed in the vicinity of mass. While dark energy is needed at cosmological scales, this table-top experiment is sensitive to this candidate. The neutron is not being screened and thus a perfect probe. The ideal suitability of UCNs for the chameleon detection has been proposed [158] and previous limits have been already improved with Gravity Resonance Spectroscopy [159, 160]. The mass of the chameleon field defines its range and the neutron mirror below the UCNs modifies the value of the field that is formed for a pressure of 10^{-4} mbar. The chameleon influences each neutron state individually thus shifting the transition frequencies in a specific way. An exact solution for chameleon fields, self-coupled through the Ratra-Peebles Potential with $\mathrm{n} = 1$ and confined between two parallel plates was presented in Ref. [161].

Other limits on chameleon fields stem from interferometer measurements. Lemmel *et al.* [162] recently presented phase shift measurements for neutron matter waves in vacuum and in low pressure helium using a method originally developed for neutron scattering lengths measurements. Li *et al.* [163] reported an upper bound on the neutron-chameleon through the relative phase shift it would induce along one of the neutron paths inside a perfect crystal neutron interferometer. The amplitude of the chameleon field was actively modulated by varying the millibar pressures inside a dual-chamber aluminum cell. So far, best limits on chameleon fields are provided by atom interferometry [164, 165]. Jaffe *et al.* [165] measure the acceleration experienced by atoms near a miniature, in-vacuum source mass using light-pulse atom interferometry.

Acknowledgments

G. K. would like to thank A. Thomas and the organizers of INPC 2016 for the opportunity to present our fundamental research with cold and ultra-cold neutrons. This work is supported by the ÖAW within the New Frontiers Groups Programme NFP 2013/09, the Austrian Science Fund under contracts No. I 531-N20, I 534-N20, I 689-N20, I 862-N20, P 26636-N20, and P 26781-N20, the German DFG as part of the Priority Programme 1491 under contract No. AB128/5-2, the French ANR under contract No. ANR-2011-ISO4-007-02, the TU Wien, and the SMI Wien.

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